Paths to the Electroweak Theory

Chris Quigg
Fermilab
quigg@fnal.gov

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Our picture of matter

Pointlike constituents ($r < 10^{-18}$ m)

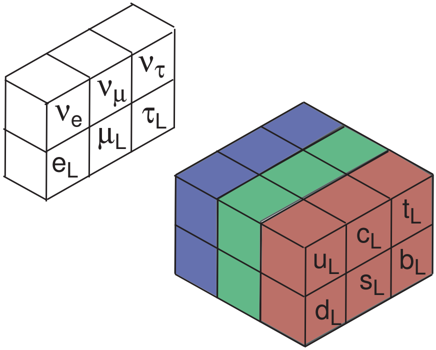
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Few fundamental forces, derived from gauge symmetries

$$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$$

Electroweak symmetry breaking: Higgs mechanism


ν_e
ν_μ
ν_τ
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μ_L
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u_L
c_L
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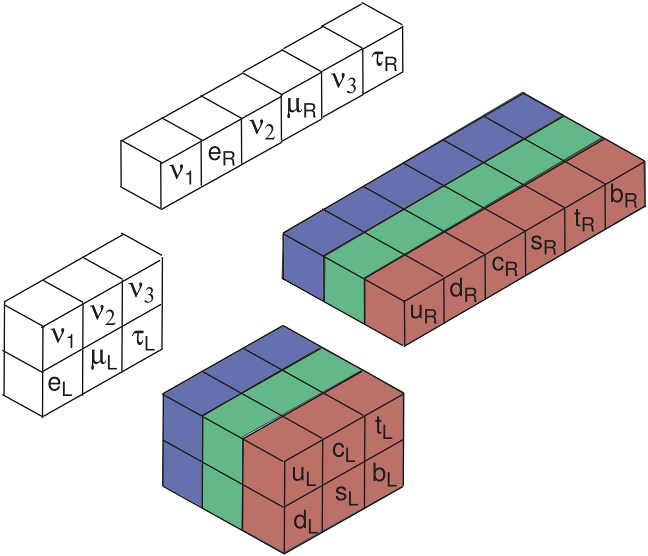
ν1
eR
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eL
μL
τL
uR
dR
cR
sR
tR
bR
uL
dL
cL
sL
tL
bL

How did we arrive here?

Discovery of β decay: H. Becquerel (1896)
—U salts fog wrapped photographic plates
Precursor: Abel Niépce de St.-Victor (1867)
Discovery of electron: J. J. Thomson (1897)

By 1905: Rutherford classifies α, β, γ radiation

$$^{\mathsf{A}}\mathsf{Z} \to {}^{\mathsf{A}}(\mathsf{Z}+1) + \beta^-$$

$$^3\mathsf{H}_1 \to {}^3\mathsf{He}_2 + \beta^-,\; n \to p + \beta^-,\; {}^{214}\mathsf{Pb}_{82} \to {}^{214}\mathsf{Bi}_{83} + \beta^-$$

Why are β^+ decays less common? Cf. ^{64}Cu

$\alpha + {}^{26}\mathsf{Al} \to {}^{30}\mathsf{P}$: F. & I. Joliot-Curie (1934)

The β-decay energy crisis

β^- spectrum is continuous: J. Chadwick (1914)

Niels Bohr, May 1930: No argument for energy conservation in β-decay. What was he thinking?

Emmy Noether (1918): *Continuous (global) symmetry of the Lagrangian implies a conservation law. Translation in space and time implies conservation of momentum and energy.* *arXiv:1902.01989*

Wolfgang Pauli, December 1930: "Dear Radioactive Ladies and Gentlemen, I have hit upon a desperate remedy regarding ...the continuous β-spectrum ..." $\boxed{\nu}$

$$^{\mathrm{A}}\mathrm{Z} \rightarrow {}^{\mathrm{A}}(\mathrm{Z}+1) + e^- + \bar{\nu}_e$$

The neutrino in theory and experiment

Christmas–New Year 1933: Fermi presents his effective theory of weak interactions, inspired by Dirac's QED and incorporating the neutrino.

Cowan, Reines, et al. (1956) observe $\bar{\nu} + p \to e^{+} + n$ at Savannah River, in rough agreement with Fermi's rate.

Parity violation in weak decays

1956 Wu *et al.*: correlation between spin vector $\vec{J}$ of polarized ^{60}Co and direction $\hat{p}_e$ of outgoing β particle

Parity leaves spin (axial vector) unchanged $\boxed{\mathcal{P} : \vec{J} \to \vec{J}}$

Parity reverses electron direction $\boxed{\mathcal{P} : \hat{p}_e \to -\hat{p}_e}$

Correlation $\vec{J} \cdot \hat{p}_e$ is *parity violating*

Late 1950s: (charged-current) weak interactions are left-handed

Parity links left-handed, right-handed ν,

$$\nu_L \xrightarrow{\Leftarrow} \mathcal{P} \xleftarrow{\Leftarrow} \cancel{\nu}_R$$

$\Rightarrow$ build a manifestly parity-violating theory with only ν_L.

Pauli's Reaction to the Downfall of Parity

Es ist uns eine traurige Pflicht,
bekannt zu geben, daß unsere
langjährige, liebe Freundin
PARITY
am 19. Januar 1957 nach kurzem
Leiden bei ~~dem~~ weiteren experimentellen
Eingriffen sanft entschlafen ist.
Für die Hinterbliebenen
e, μ, ν.

to V. Weisskopf

Pauli's Reaction to the Downfall of Parity

Es ist uns eine traurige Pflicht, bekannt zu geben, daß unsere langjährige ewige Freundin

PARITY

den 19. Januar 1957 nach kurzen Leiden bei weiteren experimentellen Eingriffen sanfte entschlafen ist.

Für die hinterbliebenen

$e \quad \mu \quad \nu$

It is our sad duty to announce that our loyal friend of many years

PARITY

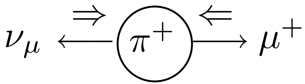
went peacefully to her eternal rest on the nineteenth of January 1957, after a short period of suffering in the face of further experimental interventions.

For those who survive her,

$e \quad \mu \quad \nu$

How do we know ν is left-handed?

▷ $\boxed{\nu_\mu}$ Measure μ^+ helicity in (spin-zero) $\pi^+ \to \mu^+\nu_\mu$



$\boxed{h(\nu_\mu) = h(\mu^+)}$ Bardon, PRL **7,** 23 (1961); Possoz, PL **70B,** 265 (1977)

μ^+ forced to have "wrong" helicity

... inhibits decay, and inhibits $\pi^+ \to e^+\nu_e$ more

$$\Gamma(\pi^+ \to e^+\nu_e)/\Gamma(\pi^+ \to \mu^+\nu_\mu) = 1.23 \times 10^{-4}$$

▷ Longitudinal pol. of recoil nucleus in $\mu^{-12}\mathrm{C}(J = 0) \to {}^{12}\mathrm{B}(J = 1)\nu_\mu$

$\boxed{\text{Infer } h(\nu_\mu) \text{ by angular momentum conservation}}$

Roesch, *Am. J. Phys.* **50**, 931 (1981)

▷ $\boxed{\nu_e}$ Measure longitudinal polarization of recoil nucleus in

$$\begin{array}{lcl} e^- \; {}^{152}\mathrm{Eu}^{\mathrm{m}}(J=0) & \rightarrow & {}^{152}\mathrm{Sm}^*(J=1)\,\nu_e \\ & & \quad \hookrightarrow \gamma\, {}^{152}\mathrm{Sm} \end{array}$$

$\boxed{\text{Infer } h(\nu_e) \text{ from } \gamma \text{ polarization}}$

Goldhaber, *Phys. Rev.* **109**, 1015 (1958)

▷ $\boxed{\nu_\tau}$ Variety of determinations in $\tau \to \pi\nu_\tau$, $\tau \to \rho\nu_\tau$, etc.

e.g., Abe, *et al.* (SLD), *Phys. Rev. Lett.* **78**, 4691 (1997)

Charge conjugation is also violated . . .

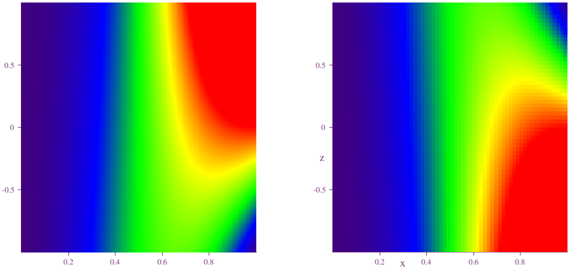
$$\nu_L \overset{\Leftarrow}{\longrightarrow} \; \mathcal{C} \; \overset{\Leftarrow}{\longrightarrow} \cancel{\bar{\nu}}_L$$

$\mu^{\pm}$ decay: angular distributions of $e^{\pm}$ reversed

$$\frac{dN(\mu^{\pm} \to e^{\pm} + \ldots)}{dxdz} = x^2(3 - 2x)\left[1 \pm z\frac{(2x-1)}{(3-2x)}\right]$$

$$x \equiv p_e/p_e^{\max},\; z \equiv \hat{s}_{\mu} \cdot \hat{p}_e$$

e^+ follows μ^+ spin $\qquad$ e^- avoids μ^- spin



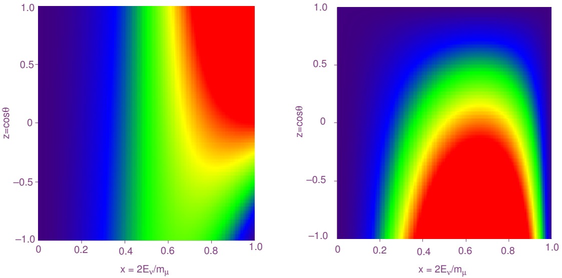
Consequences for neutrino factory

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

$$\frac{d^2 N_{\bar{\nu}_\mu}}{dxdz} = x^2[(3-2x)-(1-2x)z]\,, \quad x \equiv p_\nu / p_\nu^{\max},\ z \equiv \hat{p}_\nu \cdot \hat{s}_\mu$$

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

$$\frac{d^2 N_{\nu_e}}{dxdz} = 6x^2[(1-x)(1-z)]$$



$\boxed{\bar{\nu}_\mu}$ $\boxed{\nu_e}$

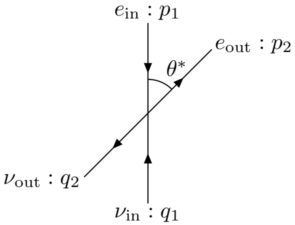
Effective Lagrangian . . .

Late 1950s: current-current interaction

$$\mathcal{L}_{V-A} = \frac{-G_F}{\sqrt{2}} \bar{\nu}\gamma_\mu(1-\gamma_5)e \; \bar{e}\gamma^\mu(1-\gamma_5)\nu + \text{h.c.}$$

$$G_F = 1.16632 \times 10^{-5} \text{ GeV}^{-2}$$

Compute $\bar{\nu}e$ scattering amplitude:



$$\mathcal{M} = -\frac{iG_F}{\sqrt{2}} \bar{v}(\nu, q_1)\gamma_\mu(1-\gamma_5)u(e, p_1) \cdot \bar{u}(e, p_2)\gamma^\mu(1-\gamma_5)v(\nu, q_2)$$

$\boxed{\bar{\nu}e \to \ \bar{\nu}e}$

$$\frac{d\sigma_{V-A}(\bar{\nu}e \to \bar{\nu}e)}{d\Omega_{\rm cm}} = \frac{\overline{|\mathcal{M}|^2}}{64\pi^2 s} = \frac{G_F^2 \cdot 2mE_\nu (1-z)^2}{16\pi^2} \quad z = \cos\theta^*$$

$$\sigma_{V-A}(\bar{\nu}e \to \bar{\nu}e) = \frac{G_F^2 \cdot 2mE_\nu}{3\pi}$$

$$\approx 0.574 \times 10^{-41}\ \text{cm}^2 \left(\frac{E_\nu}{1\ \text{GeV}}\right)$$

Small! $\approx 10^{-14}\,\sigma(pp)$ at 100 GeV

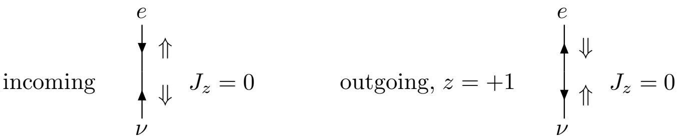
$\boxed{\nu e \to \ \nu e}$

$$\frac{d\sigma_{V-A}(\nu e \to \nu e)}{d\Omega_{\rm cm}} = \frac{G_F^2 \cdot 2mE_\nu}{4\pi^2}$$

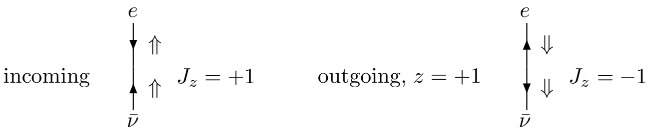
$$\sigma_{V-A}(\nu e \to \nu e) = \frac{G_F^2 \cdot 2mE_\nu}{\pi}$$

$$\approx 1.72 \times 10^{-41}\ \text{cm}^2 \left(\frac{E_\nu}{1\ \text{GeV}}\right)$$

Why 3× difference?



allowed at all angles



forbidden (angular momentum) at $z = +1$

1962: Lederman, Schwartz, Steinberger $\nu_\mu \neq \nu_e$

- ▷ Make HE $\pi \to \mu\nu$ beam
- ▷ Observe $\nu N \to \mu +$ anything
- ▷ Don't observe $\nu N \to e +$ anything

Danby, *et al.*, *Phys. Rev. Lett.* **9**, 36 (1962)

Suggests family structure

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$$

$\approx$ no interactions known to cross boundaries

Generalize effective (current-current) Lagrangian:

$$\mathcal{L}_{V-A}^{(e\mu)} = \frac{-G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma_\mu (1 - \gamma_5) \mu \; \bar{e} \gamma^\mu (1 - \gamma_5) \nu_e + \text{h.c.} \; ,$$

Compute muon decay rate

$$\Gamma(\mu \to e \bar{\nu}_e \nu_\mu) = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

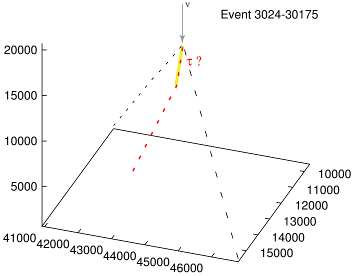
accounts for the 2.2-μs muon lifetime

2000: DONuT Three-Neutrino Experiment

- Prompt (beam-dump) ν_τ beam produced in

$$D_s^+ \;\to\; \tau^+\nu_\tau$$
$$\hookrightarrow X^+\bar{\nu}_\tau$$

- Observe $\nu_\tau N \to \tau +$ anything in emulsion; τ lifetime is 0.3 ps



Candidate event in ECC1. The three tracks with full emulsion data are shown. The red track shows a 100 mrad kink 4.5mm from the interaction vertex. The scale units are microns.

Kodama, *et al.*, *Phys. Lett.* **B504**, 218 (2001)

Cross section for inverse muon decay

$$\sigma(\nu_\mu e \to \mu \nu_e) = \sigma_{V-A}(\nu_e e \to \nu_e e)\left[1 - (m_\mu^2 - m_e^2)/2m_e E_\nu\right]^2$$

agrees with CHARM II, CCFR data ($E_\nu \lesssim 600$ GeV)

$$\boxed{\text{PW unitarity: } |\mathcal{M}_J| < 1}$$

$$V - A \text{ theory:} \quad \mathcal{M}_0 = \frac{G_F \cdot 2m_e E_\nu}{\pi\sqrt{2}}\left[1 - \frac{(m_\mu^2 - m_e^2)}{2m_e E_\nu}\right]$$

satisfies pw unitarity for

$$E_\nu < \pi / G_F m_e \sqrt{2} \approx 3.7 \times 10^8 \text{ GeV}$$

$$\boxed{\Rightarrow V - A \text{ theory cannot be complete}}$$

Physics must change below $\sqrt{s} \approx 600$ GeV

Universal weak couplings: *Rough and ready test*

Fermi constant from muon decay

$$G_\mu = \left[\frac{192\pi^3\hbar}{\tau_\mu m_\mu^5}\right]^{\frac{1}{2}} = 1.1638 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

Meticulous analysis yields $G_\mu = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2}$

Fermi constant from tau decay

$$G_\tau = \left[\frac{\Gamma(\tau \to e\bar{\nu}_e\nu_\tau)}{\Gamma(\tau \to \mathrm{all})}\frac{192\pi^3\hbar}{\tau_\tau m_\tau^5}\right]^{\frac{1}{2}} = 1.1642 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

Excellent agreement with $G_\beta = 1.16639(2) \times 10^{-5}\ \mathrm{GeV}^{-2}$

Charged currents acting in leptonic and semileptonic interactions are of universal strength; $\Rightarrow$ *universality of current-current form, or whatever lies behind it*

Formulate electroweak theory

Three crucial clues from experiment:

- Left-handed weak-isospin doublets,

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s' \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b' \end{pmatrix}_L ;$$

- Universal strength of the (charged-current) weak interactions;
- Idealization that neutrinos are massless.

First two clues suggest $SU(2)_L$ gauge symmetry

The Idea of Gauge Theories

Noether's Theorem II: Imposing a continuous symmetry *locally* implies a theory with interactions mediated by gauge bosons that couple to the conserved current d.

Hermann Weyl (1918–1929): Derive QED from a local QM phase symmetry. Charge is conserved. Photon is massless.

C. N. Yang and Robert Mills (1954): Proposed a gauge theory of nuclear forces based on local isospin symmetry. Massless vector bosons.

Isospin-SU(2) $\rightarrow$ color-SU(3): $\rightsquigarrow$ QCD (early 1970s)

Through 1950s and 1960s . . .

Continued interest in a Yang–Mills Theory of nuclear forces.

After $V - A$ description of weak interactions, interest in a gauge theory of weak interactions. Several gauge groups tried. Glashow explored $\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$

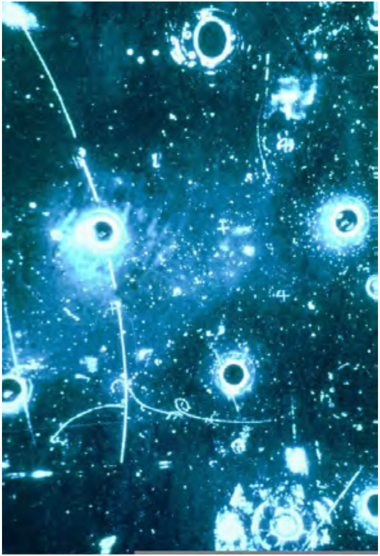
Two challenges: massive weak bosons, massive fermions.

Mass term $\mathcal{L}_e = -m_e(\bar{e}_\mathrm{R} e_\mathrm{L} + \bar{e}_\mathrm{L} e_\mathrm{R}) = -m_e \bar{e} e$ violates local gauge invariance. Slide 4.

Key insights: hidden symmetries, Meissner effect.
Brout, Englert, Higgs, Guralnik, Hagen, Kibble (1964)
Weinberg (1967) combined with $\mathrm{SU(2)} \otimes \mathrm{U(1)}$

- Electromagnetism is mediated by a massless photon, coupled to the electric charge;
- Mediator of charged-current weak interaction acquires a mass $M_W^2 = \pi\alpha / G_F\sqrt{2}\sin^2\theta_W$,
- Mediator of (new!) neutral-current weak interaction acquires mass $M_Z^2 = M_W^2/\cos^2\theta_W$;
- Massive neutral scalar particle, the Higgs boson, appears, but its mass is not predicted;
- Fermions can acquire mass—values not predicted.

Gargamelle $\bar{\nu}_\mu e$ event (1973)

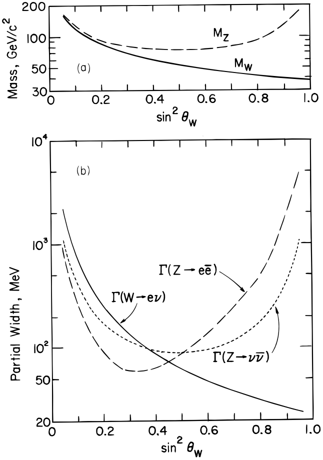


- Electromagnetism is mediated by a massless photon, coupled to the electric charge;
- Mediator of charged-current weak interaction acquires a mass $M_W^2 = \pi\alpha / G_F\sqrt{2}\sin^2\theta_W$,
- Mediator of (new!) neutral-current weak interaction acquires mass $M_Z^2 = M_W^2/\cos^2\theta_W$;
- Massive neutral scalar particle, the Higgs boson, appears, but its mass is not predicted;
- Fermions can acquire mass—values not predicted.

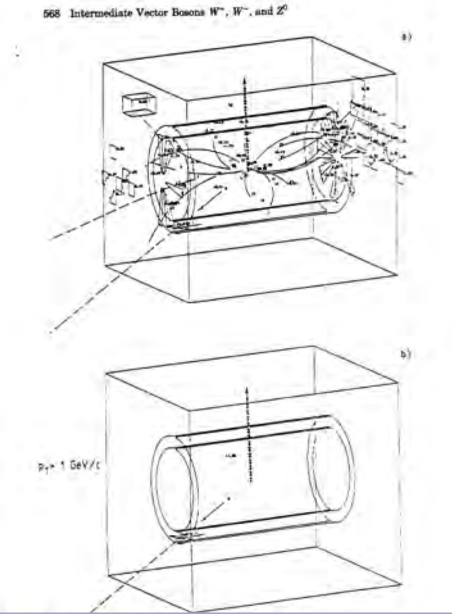
Determine $\sin^2\theta_W$ to predict M_W, M_Z

With a measurement of $\sin^2\theta_W$, predict

$M_W^2 = \pi\alpha/G_F\sqrt{2}\sin^2\theta_W \approx (37.28\ \mathrm{GeV}/c^2)^2/\sin^2\theta_W \quad M_Z^2 = M_W^2/\cos^2\theta_W$



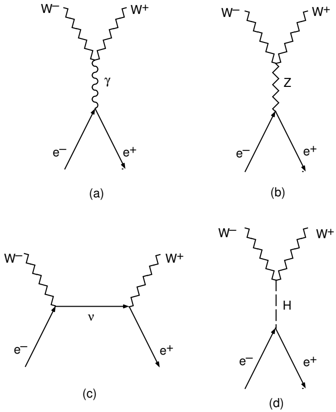
First Z from UA1



Why a Higgs boson must exist

▷ Role in canceling high-energy divergences

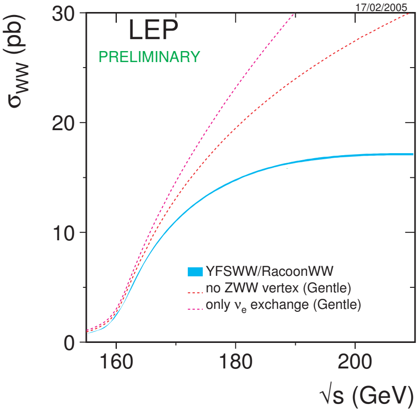
S-matrix analysis of $e^+e^- \to W^+W^-$

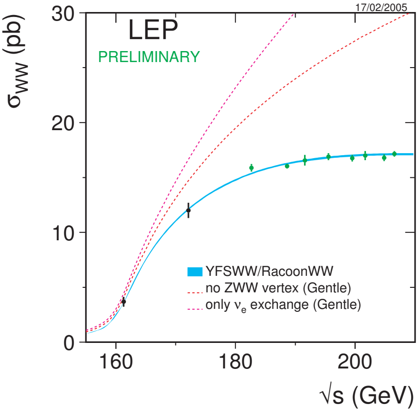


Individual $J = 1$ partial-wave amplitudes $\mathcal{M}_\gamma^{(1)}$, $\mathcal{M}_Z^{(1)}$, $\mathcal{M}_\nu^{(1)}$ have unacceptable high-energy behavior ($\propto s$)

...But sum is well-behaved

"Gauge cancellation" observed at LEP2 (Tevatron)





$J = 0$ amplitude exists because electrons have mass, and can be found in “wrong” helicity state

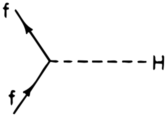
$$\mathcal{M}_\nu^{(0)} \propto s^{\frac{1}{2}} \quad \text{: unacceptable HE behavior}$$

(no contributions from γ and Z)

This divergence is canceled by the Higgs-boson contribution

$$\boxed{\Rightarrow He\bar{e} \text{ coupling must be} \propto m_e,}$$

because “wrong-helicity” amplitudes $\propto m_e$



$$\frac{-im_f}{v} = -im_f(G_F\sqrt{2})^{1/2}$$

If the Higgs boson did not exist, something else would have to cure divergent behavior

If gauge symmetry were unbroken . . .

- no Higgs boson
- no longitudinal gauge bosons
- no extreme divergences
- no wrong-helicity amplitudes

. . . and no viable low-energy phenomenology

In spontaneously broken theory . . .

- gauge structure of couplings eliminates the most severe divergences
- lesser—but potentially fatal—divergence arises because the electron has mass . . . due to the Higgs mechanism
- SSB provides its own cure—the Higgs boson

Similar interplay & compensation *must exist* in any acceptable theory

The importance of the 1-TeV scale

EW theory does not predict Higgs-boson mass

▷ Conditional *upper bound* from Unitarity

Compute amplitudes $\mathcal{M}$ for gauge boson scattering at high energies, make a partial-wave decomposition Most channels decouple – pw amplitudes are small at all energies (except very near the particle poles, or at exponentially large energies) – $\forall M_H$.

Four interesting channels:

$$W_L^+ W_L^- \quad Z_L^0 Z_L^0/\sqrt{2} \quad HH/\sqrt{2} \quad HZ_L^0$$

L: longitudinal, $1/\sqrt{2}$ for identical particles

Condition for Partial-wave unitarity $|a_0| \leq 1$

$$\Longrightarrow \quad M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 1\ \mathrm{TeV}/c^2$$

- If the bound is respected
  - weak interactions remain weak at all energies
  - perturbation theory is everywhere reliable

- If the bound is violated
  - perturbation theory breaks down
  - weak interactions among $W^{\pm}$, Z, H become strong on 1-TeV scale

$\Rightarrow$ features of *strong* interactions at GeV energies will characterize *electroweak* gauge boson interactions at TeV energies

New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

Electroweak interactions of quarks (one generation)

- Left-handed doublet

$$\begin{array}{lccc} & I_3 & Q & Y = 2(Q - I_3) \\ \mathsf{L}_q = \begin{pmatrix} u \\ d \end{pmatrix}_L & \begin{array}{c} \frac{1}{2} \\ -\frac{1}{2} \end{array} & \begin{array}{c} +\frac{2}{3} \\ -\frac{1}{3} \end{array} & \frac{1}{3} \end{array}$$

- two right-handed singlets

$$\begin{array}{lccc} & I_3 & Q & Y = 2(Q - I_3) \\ \mathsf{R}_u = u_R & 0 & +\frac{2}{3} & +\frac{4}{3} \\ \mathsf{R}_d = d_R & 0 & -\frac{1}{3} & -\frac{2}{3} \end{array}$$

Electroweak interactions of quarks

- CC interaction

$$\mathcal{L}_{W\text{-}q} = \frac{-g}{2\sqrt{2}} \left[\bar{u}\gamma^{\mu}(1-\gamma_5)d\, W_{\mu}^{+} + \bar{d}\gamma^{\mu}(1-\gamma_5)u\, W_{\mu}^{-} \right]$$

identical in form to $\mathcal{L}_{W\text{-}\ell}$: universality $\Leftrightarrow$ weak isospin

- NC interaction

$$\mathcal{L}_{Z\text{-}q} = \frac{-g}{4\cos\theta_W} \sum_{i=u,d} \bar{q}_i\gamma^{\mu} \left[L_i(1-\gamma_5) + R_i(1+\gamma_5) \right] q_i Z_{\mu}$$

$$L_i = \tau_3 - 2Q_i \sin^2\theta_W \quad R_i = -2Q_i \sin^2\theta_W$$

equivalent in form (not numbers) to $\mathcal{L}_{Z\text{-}\ell}$

Trouble in Paradise

Universal $u \leftrightarrow d$, $\nu_e \leftrightarrow e$ *not quite right*

$$\text{Good:} \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \to \text{Better:} \quad \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$$

$$d_\theta \equiv d\,\cos\theta_C + s\,\sin\theta_C \qquad \cos\theta_C = 0.9736 \pm 0.0010$$

"Cabibbo-rotated" doublet perfects CC interaction (up to small third-generation effects) but $\Rightarrow$ serious trouble for NC

$$\begin{aligned}
\mathcal{L}_{Z\text{-}q} \;=\; & \frac{-g}{4\cos\theta_W} Z_\mu \left\{ \bar{u}\gamma^\mu \left[L_u(1-\gamma_5) + R_u(1+\gamma_5) \right] u \right. \\
& + \bar{d}\gamma^\mu \left[L_d(1-\gamma_5) + R_d(1+\gamma_5) \right] d\,\cos^2\theta_C \\
& + \bar{s}\gamma^\mu \left[L_d(1-\gamma_5) + R_d(1+\gamma_5) \right] s\,\sin^2\theta_C \\
& + \bar{d}\gamma^\mu \left[L_d(1-\gamma_5) + R_d(1+\gamma_5) \right] s\,\sin\theta_C\cos\theta_C \\
& \left. + \,\bar{s}\gamma^\mu \left[L_d(1-\gamma_5) + R_d(1+\gamma_5) \right] d\,\sin\theta_C\cos\theta_C \right\}
\end{aligned}$$

Glashow–Iliopoulos–Maiani

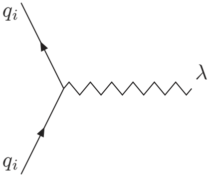
two LH doublets: $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \qquad \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L \quad \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L$

$$(s_\theta = s \cos\theta_C - d \sin\theta_C)$$

$+$ right-handed singlets, e_R, μ_R, u_R, d_R, c_R, s_R

$\boxed{\text{Required new charmed quark, } c}$

Cross terms vanish in $\mathcal{L}_{Z\text{-}q}$,



$$\frac{-ig}{4\cos\theta_W}\gamma_\lambda[(1-\gamma_5)L_i + (1+\gamma_5)R_i] \quad ,$$

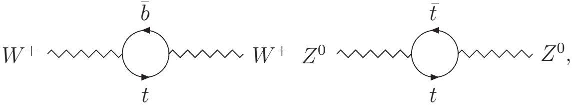
$$L_i = \tau_3 - 2Q_i \sin^2\theta_W \quad R_i = -2Q_i \sin^2\theta_W$$

flavor-diagonal interaction!

Experimental clues to the Higgs-boson mass

Sensitivity of EW observables to m_t gave early indications for massive top

Quantum corrections to SM predictions for M_W and M_Z arise from different quark loops



$$\ldots\text{alter the link } \underbrace{M_W^2}_{(80.398 \pm 0.025\ \text{GeV})^2} = \underbrace{M_Z^2\left(1 - \sin^2\theta_W\right)}_{(80.939\ \text{GeV})^2}(1 - \Delta\rho)$$

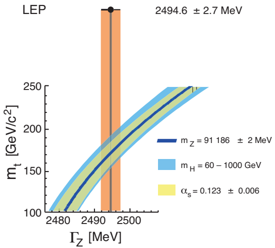
where $\Delta\rho \approx \Delta\rho^{(\text{quarks})} = 3G_F m_t^2/8\pi^2\sqrt{2}$

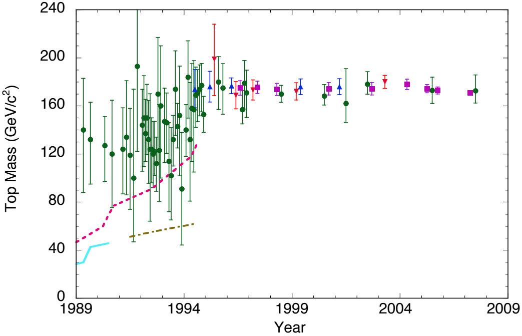
Strong dependence on m_t^2 accounts for precision of m_t estimates derived from EW observables

Tevatron: $\delta m_t/m_t \approx 1.28\%$... Look beyond quark loops to next most important quantum corrections: $\boxed{\textit{Higgs-boson effects}}$

Global fits to precision EW measurements

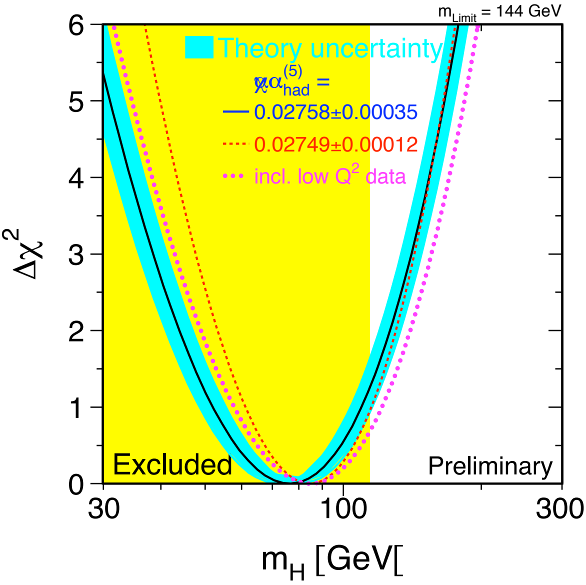
- precision improves with time / calculations improve with time



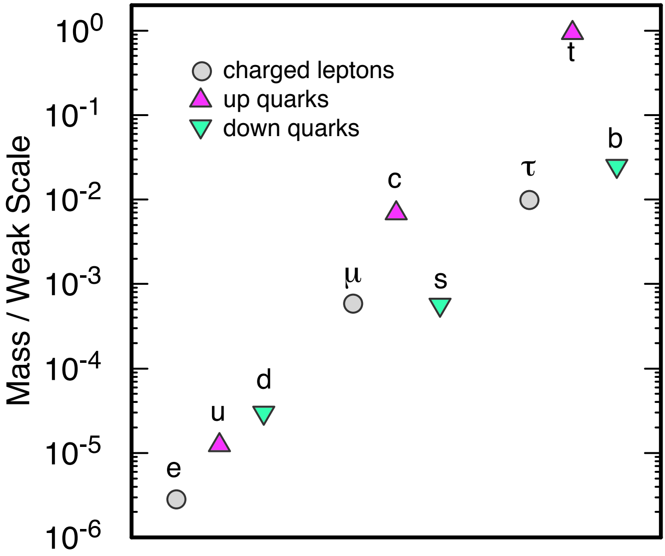


11.94, LEPEWWG: $m_t = 178 \pm 11^{+18}_{-19}$ GeV/c^2

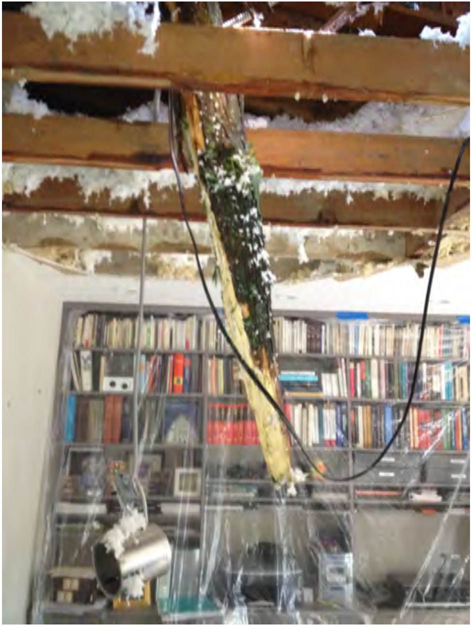
Direct measurements: $m_t = 170.9 \pm 1.8$ GeV/c^2


m_Limit = 144 GeV
Theory uncertainty
Δα(5) had =
0.02758±0.00035
0.02749±0.00012
incl. low Q2 data
Excluded
Preliminary
Δχ2
6
5
4
3
2
1
0
30
100
300
mH [GeV[

Yukawa couplings (mass eigenstates) ζ_f^{diag}



July 1, 2012



What LHC has taught us about the Higgs Boson

Evidence is developing as it would for a "standard-model" Higgs boson

Unstable neutral particle with $M_H = 125.10 \pm 0.14$ GeV

Decays to W^+W^-, ZZ implicate H as agent of EWSB

Decay to $\gamma\gamma$ as expected (loop-level)   Indirect constraint on Γ_H

Dominant spin-parity $J^P = 0^+$

$Ht\bar{t}$ coupling from gg fusion, $t\bar{t}H$ production link to fermion mass origin

$\tau^+\tau^-$ and $b\bar{b}$ at expected rates

Only third-generation fermion couplings observed; $\mu^+\mu^-$ evidence

reconnaissance $\rightsquigarrow$ search-and-discovery $\rightsquigarrow$ forensic investigation

Questions about EWSB and the Higgs Sector

1. Is $H(125)$ the only member of its clan? Might there be others—charged or neutral—at higher or lower masses?
2. Does $H(125)$ fully account for electroweak symmetry breaking? Does it match standard-model branching fractions to gauge bosons? Are absolute couplings to W and Z as expected in the standard model?
3. All production rates as expected? Surprise sources of $H(125)$?
4. What accounts for the immense range of fermion masses?
5. Is the Higgs field the only source of fermion masses? Are fermion couplings proportional to fermion masses? How can we detect $H \to c\bar{c}$? e^+e^-?? (basis of chemistry)
6. What role does the Higgs field play in generating neutrino masses?

More questions about EWSB and the Higgs Sector

7. Can we establish or exclude decays to new particles? Does $H(125)$ act as a portal to hidden sectors? When can we measure Γ_H?
8. Do loop-induced decays ($gg, \gamma\gamma, \gamma Z$) occur at standard-model rates?
9. What can we learn from rare decays ($J/\psi\,\gamma, \Upsilon\,\gamma, \ldots$)?
10. Does the EW vacuum seem stable, or suggest a new physics scale?
11. Can we find signs of new strong dynamics or (partial) compositeness?
12. Can we establish the HHH trilinear self-coupling?
13. How well can we test the notion that H regulates Higgs–Goldstone scattering, i.e., tames the high-energy behavior of WW scattering?
14. Is the electroweak phase transition first-order?

See Dawson, Englert, Plehn, arXiv:1808.01324 $\rightsquigarrow$ *Phys. Rep.*

Fermion mass is accommodated, not explained

- All fermion masses $\sim$ physics beyond the standard model!
- $\zeta_t \approx 1 \qquad \zeta_e \approx 3 \times 10^{-6} \qquad \zeta_\nu \approx 10^{-10}$??

  What accounts for the range and values of the Yukawa couplings?
- There may be *other sources* of neutrino mass